Cross-section measurements with meson decay at rest neutrino beams

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WINP2015@BNL
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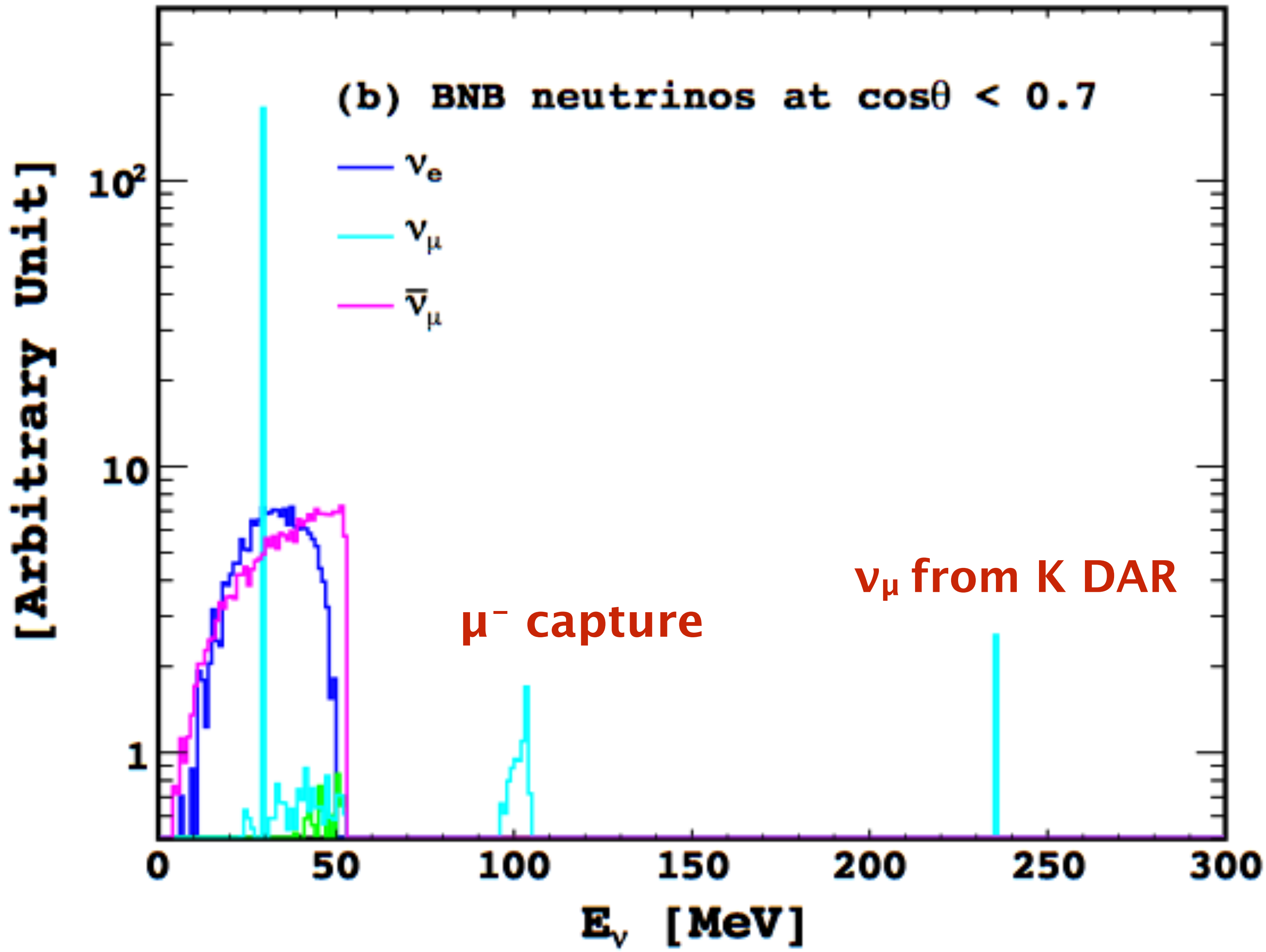
Potential pion-DAR neutrino sources

	LANCE	BNB	ISIS	SNS	MFL	ESS
Location	US(LANL)	US(FNAL)	UK(RAL)	US(ORNL)	JP(JPARK)	Sweden
Power	**56kW**	**36kW**	**160kW**	**>1MW**	**1MW**	**5MW**
Rep.Rate	-	5Hz	50Hz	60Hz	25Hz	50Hz
p-Energy	0.8GeV	8GeV	0.8GeV	1.4GeV	3GeV	1.3GeV
Beam T	Continuous	**1.6us**	**200ns**	**380ns**	**1us**	**1.4us**
Target	Various	Beryllium	Tantalum	Mercury	Mercury	Mercury
ν-Proposal		CENNS CAPTAIN		OscSNS COHERENT	P56	

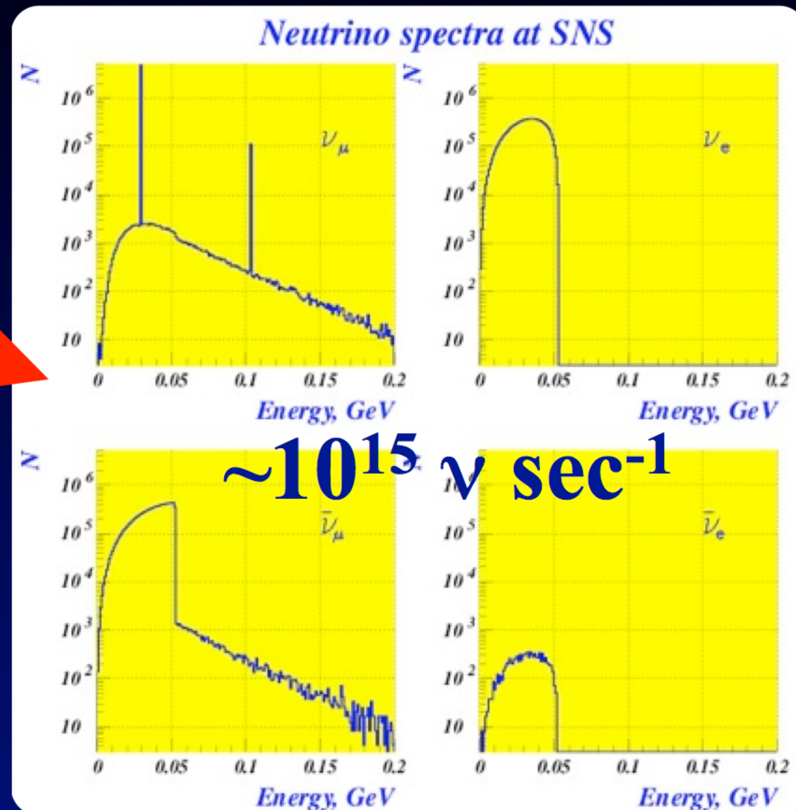
* Daedalus (a larger future initiative)

Meson Decay-At-Rest Neutrino Source



- ν–flux is about 10^6 to 10^7 neutrinos/cm^2/s/flavor
  (depends on the beam power and the dist. from target)

Why (Core-Collapse) Supernova People like SNS?



SNS looks like a mini-CCSN, producing many neutrinos of tens of MeV.

This allows an experimental program to measure neutrino cross sections of interest for supernovae.

Segmented detector for **Solid targets**

^{51}V, ^{27}Al, ^{9}Be, ^{11}B, ^{52}Cr, ^{56}Fe, ^{59}Co, ^{209}Bi, ^{181}Ta

Homogeneous detector for **Liquid targets**

^{2}H, ^{12}C, ^{16}O, ^{127}I

W. R. Hix, ν@SNS, Oak Ridge, May 2012

Sterile neutrinos and neutrino oscillations

- Lower energy requires shorter distance for neutrino oscillation study
  → neutrino oscillation effect within a detector

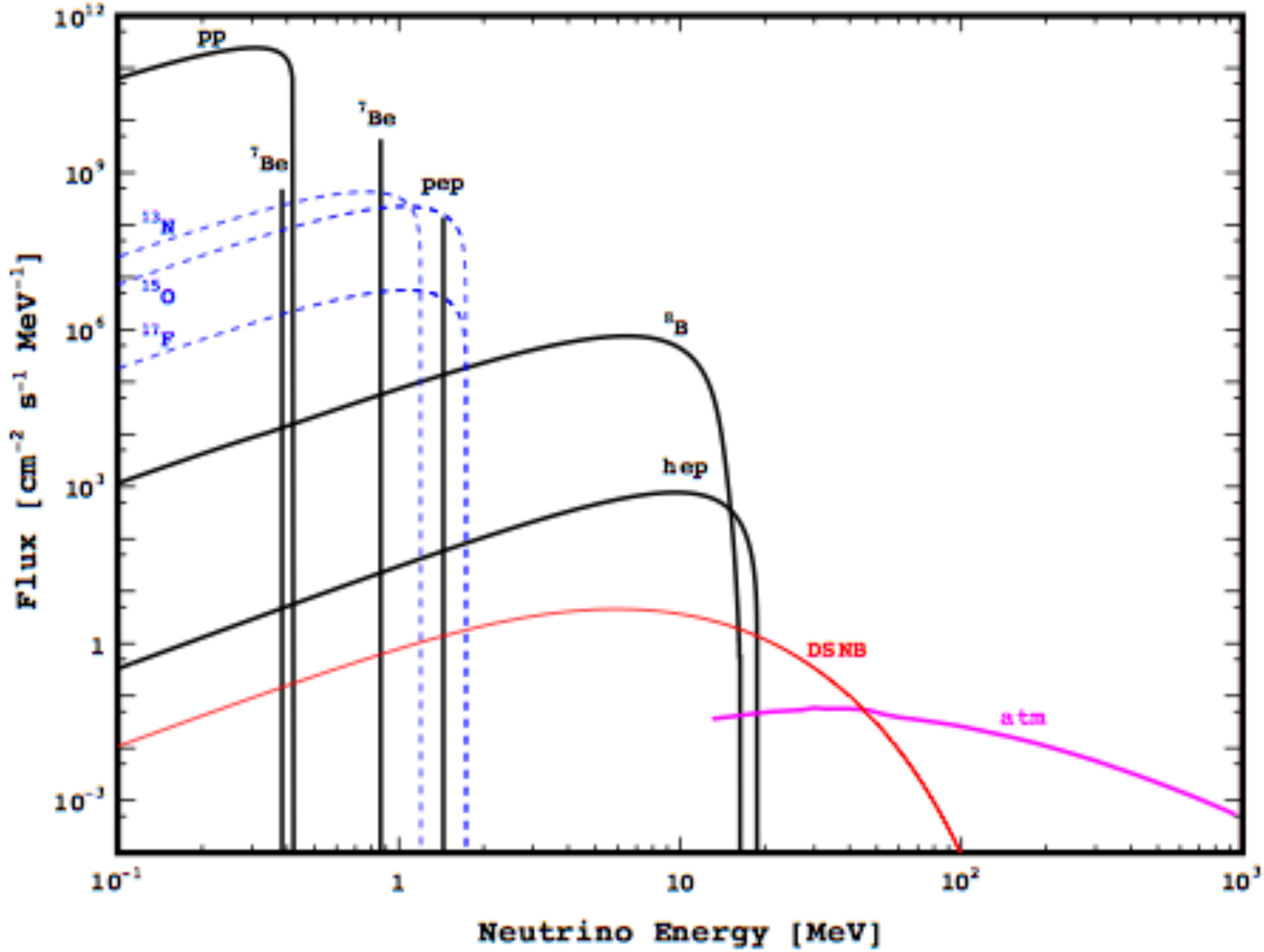
Coherent Elastic Neutrino Nucleus Scattering

- Background of dark matter search
- Neutron form factor
- Neutrino magnetic moment
- Test weak mixing angle
- Non Standard Model Interactions

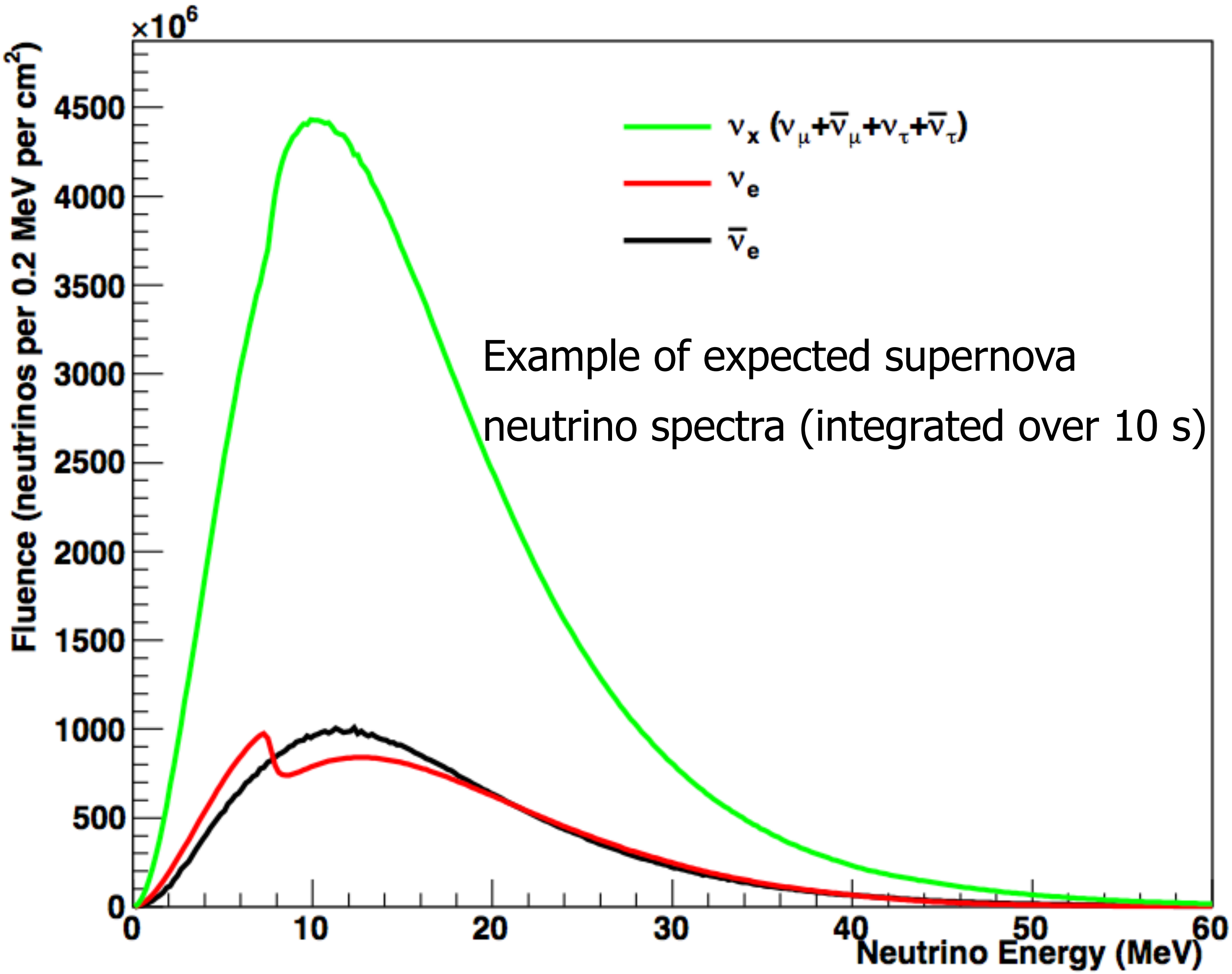
Core collapse supernova physics

- Understanding the supernova explosion precess
- Supernova neutrino detection process
- Only a couple of v-N cross sections are measured in SN energy range

Neutrinos from Astrophysical Origin

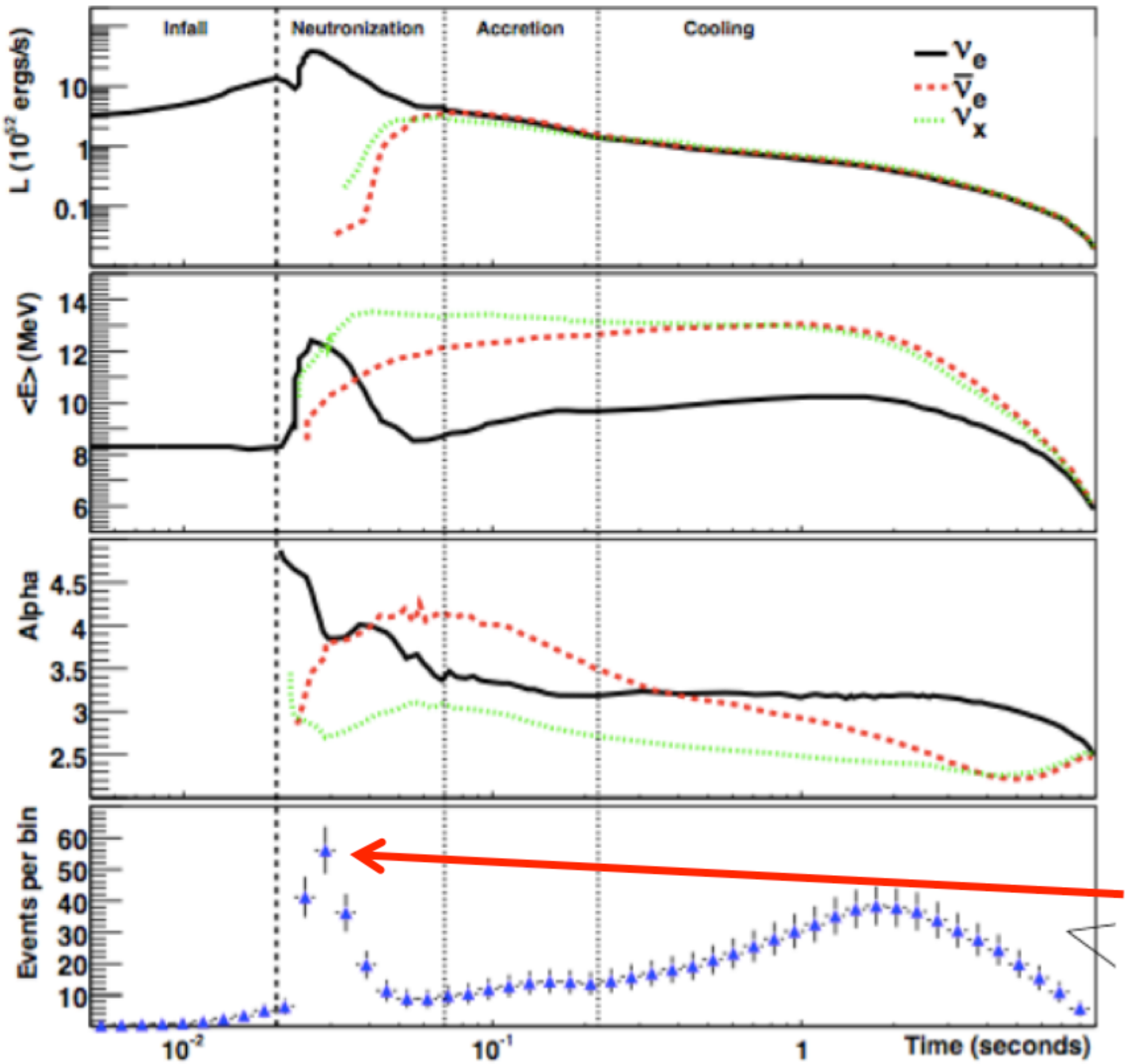


Neutrinos from Astrophysical Origin



Detection of the SN Neutronization Burst: ν_e Sensitivity

$$p + e^- \rightarrow n + \nu_e$$



Burst is only 20 ms long and is essentially all ν_e

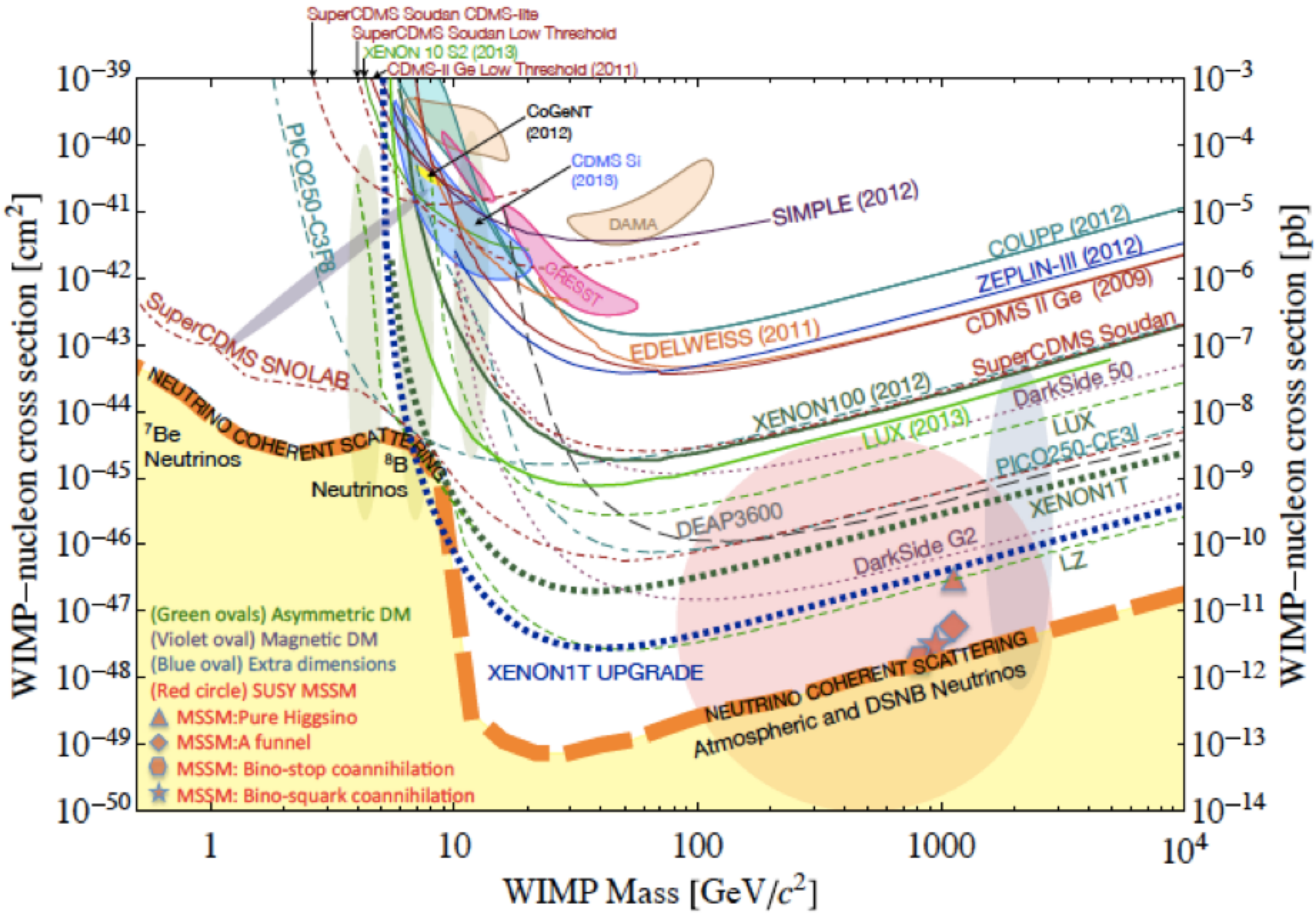
Mean energy of events is low, 10–12 MeV

IMB/Kamiokande detected higher energy cooling neutrinos, not neutrinos from the neutronization process

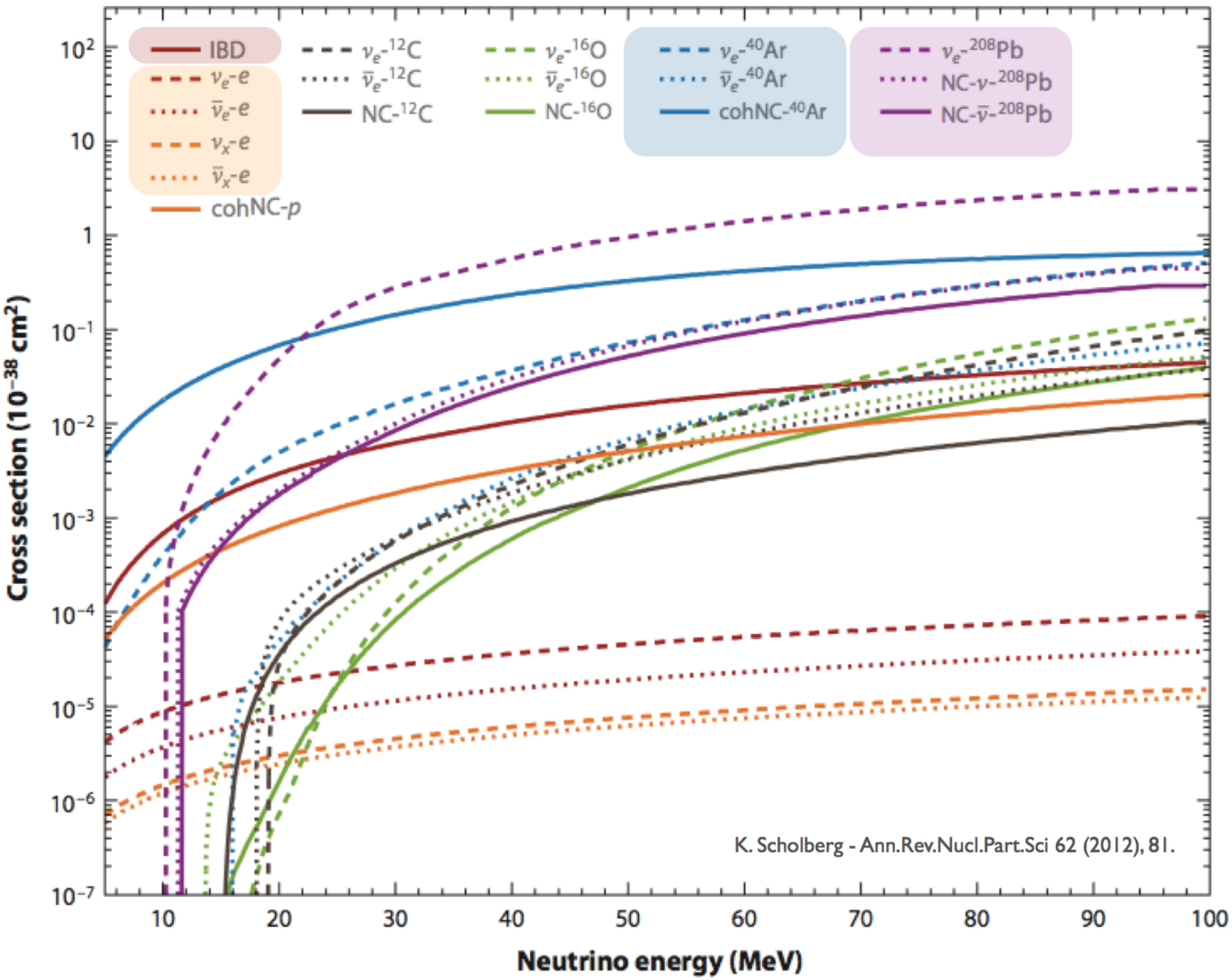
Potential for ν_e detection in liquid argon by ELBNF

I.Stancu

Irreducible Background of Dark Matter Search



Cross-sections below 100MeV



- Inverse beta decay (IBD), ν-e scattering known at few % level
- ^{12}C is the only heavy nucleus with xsec well measured : ~10% level

Cross-section

- CEvNS process (Dark Matter Experiments)
- ν on Argon nuclei (ELBNF – Supernova detection)
- ν on Lead (and iron) nuclei (HALO…)
- ν on Oxygen nuclei (SuperK/HyperK…)
- Requests from the Supernova physicists …

Event Rate = [ν–Flux] x $\boxed{\text{[Cross section]}}$ x [Det.Resp]

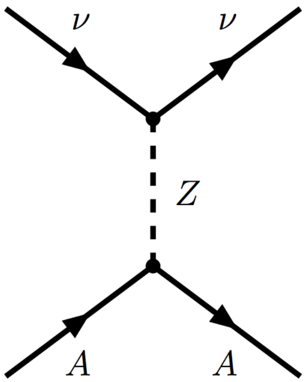
100~1000 evts/year

10~15% (?)
ν source uncertainties

a few %
uncertainties?

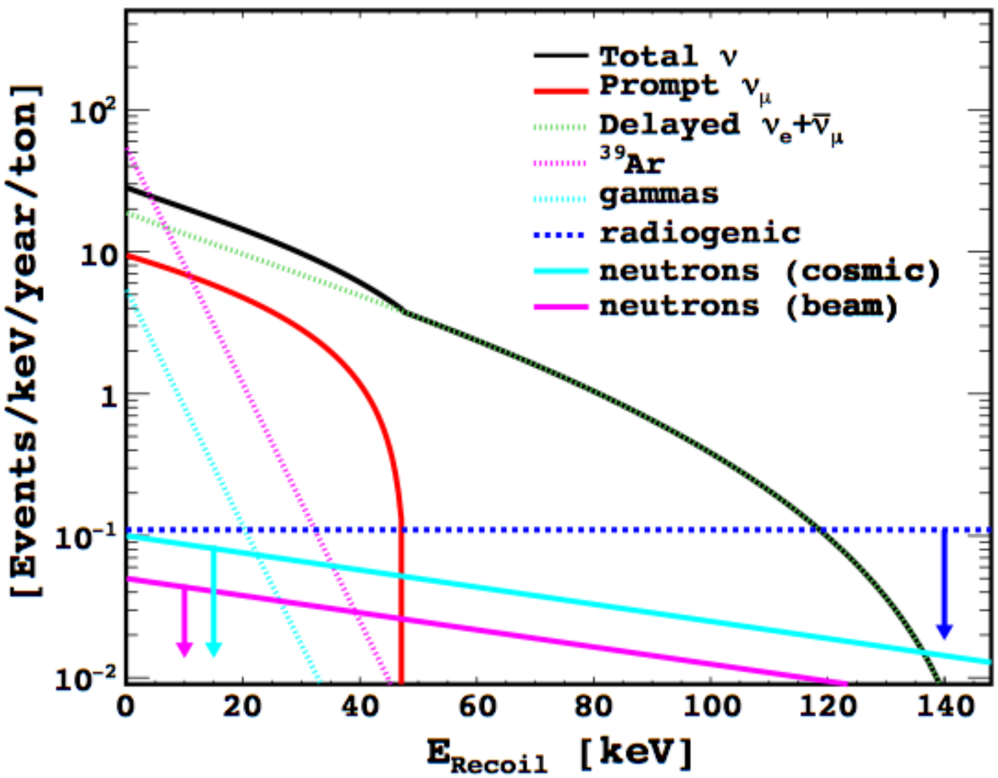
- Are neutrino sources (π–DAR) available for these exp?
- Are detector technologies available?
- Independent measurement of the neutrino flux?

Coherent Elastic Neutrino Nucleus Scattering

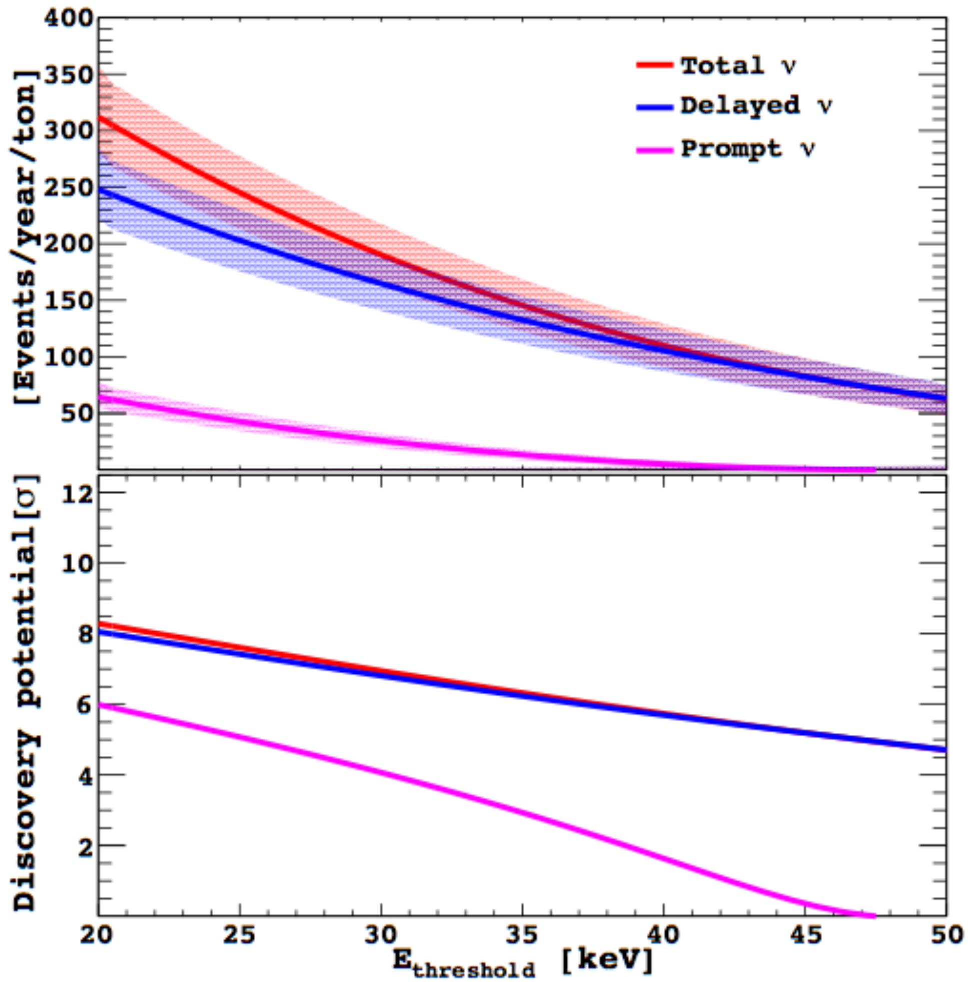


$$\sigma_{\nu N} \simeq \frac{4}{\pi} E_\nu^2 \left[Z\omega_p + (A - Z)\omega_n \right]^2$$

$$E_\nu < \frac{1}{R_N} \simeq 50 \text{ MeV}$$



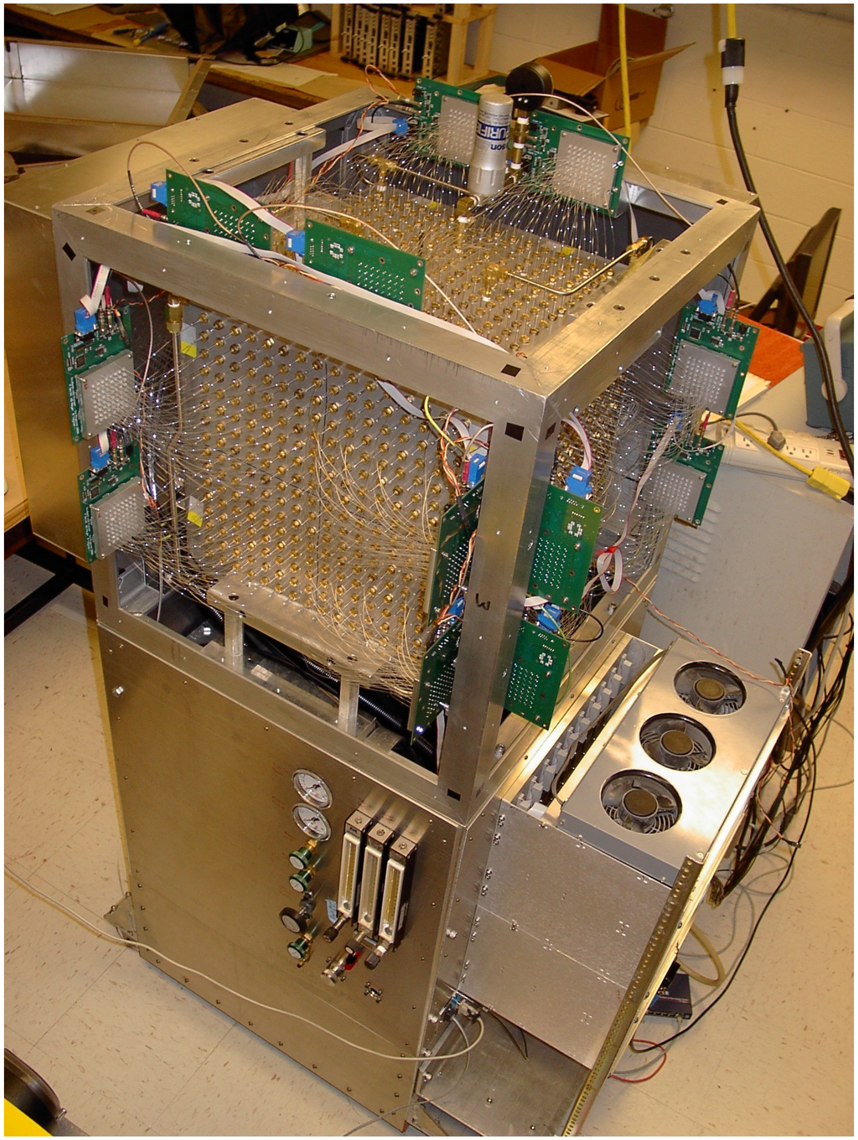
CENNS Discovery Potential at BNB

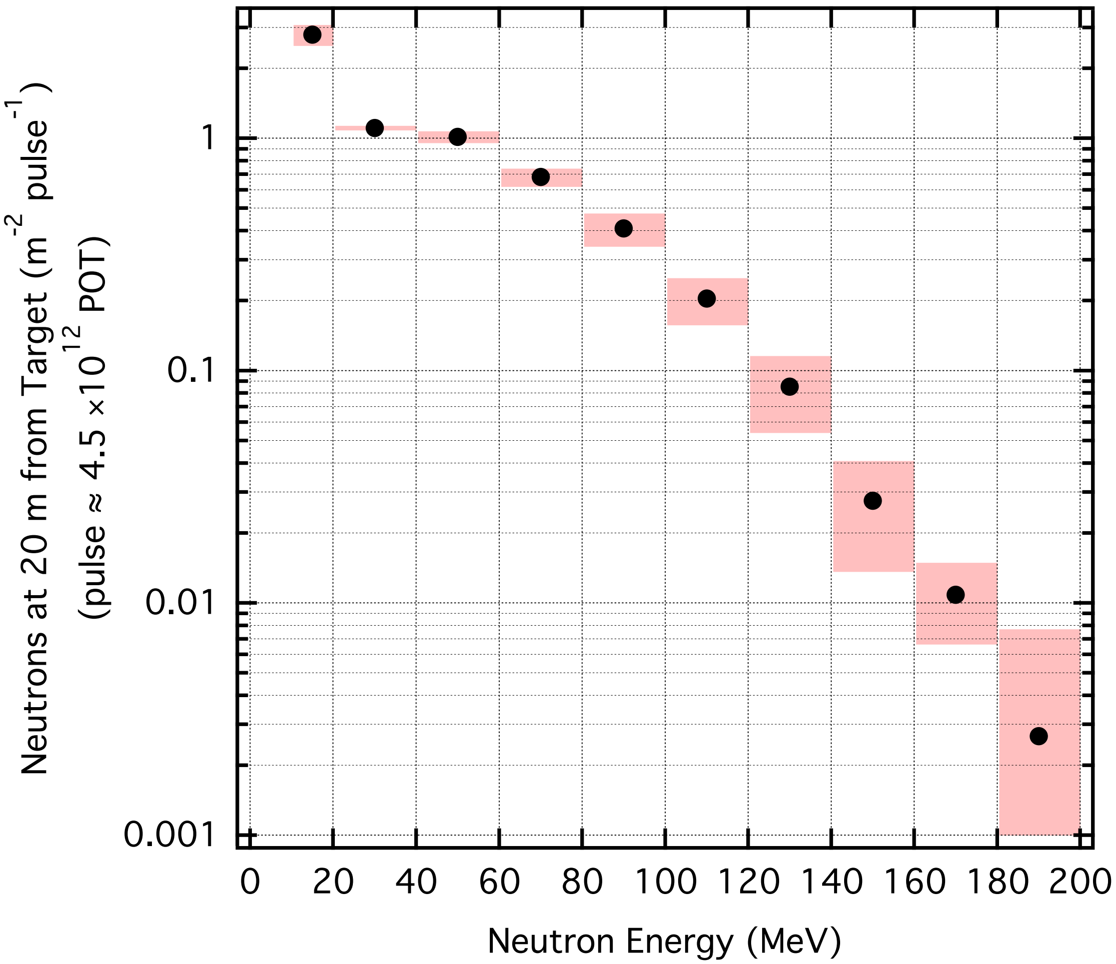


7.5σ discovery at 25 keV energy threshold

Phys. Rev. D 89, 072004 (2014)

Measured neutron spectrum at BNB (FNAL)

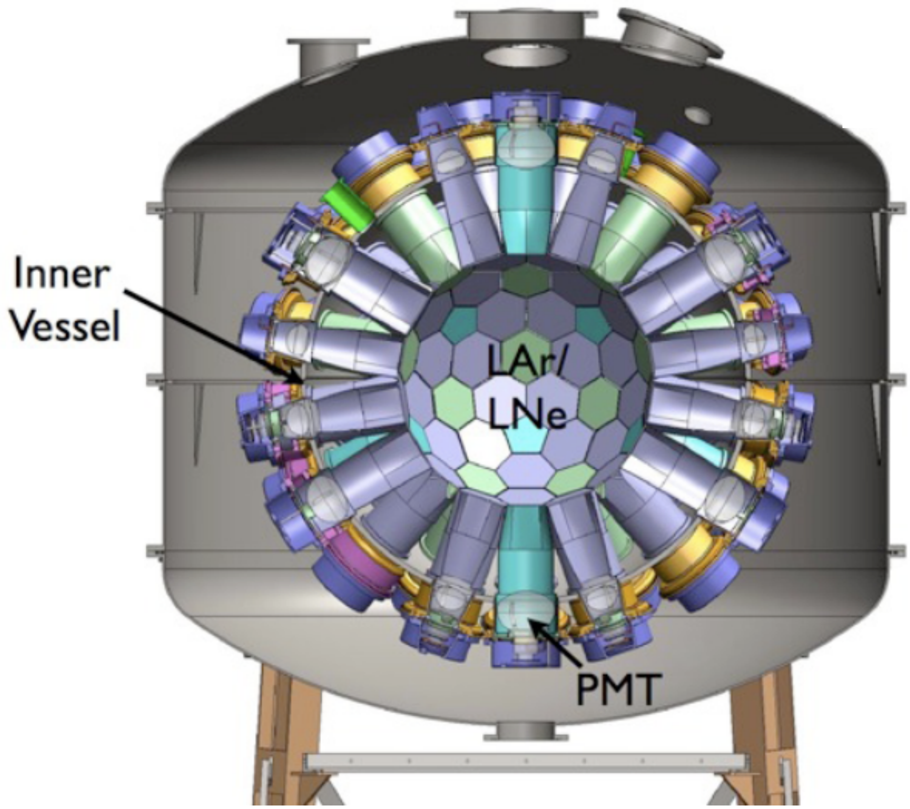




- SciBath (Indiana Univ. R.Tayloe)
- 82L volume mineral oil
- 768 wavelengh shifting fibers

- Neutron flux measurement
  20m from the BNB target (backward)

MiniCLEAN for CENNS



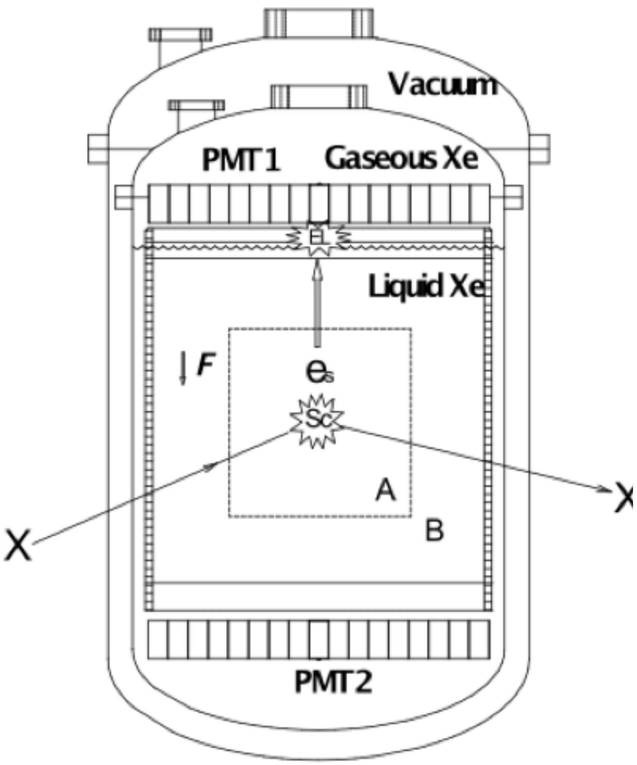
- **MiniCLEAN detector at SNOLab**
  - Dark matter search
  - Particle Astrophysics
  - Single phase LAr detector
  - Pulse shape discrimination
  - Plan to run at SNOLab until 2017

- **MiniCLEAN detector at pion-DAR**
  - Perfect fit for CENNS measurement
  - 500kg fiducial for CENNS
  - Less stringent BG constraint for cross-section measurement (duty factor ~10^{-5})
  - ~10% measurement of Xsec

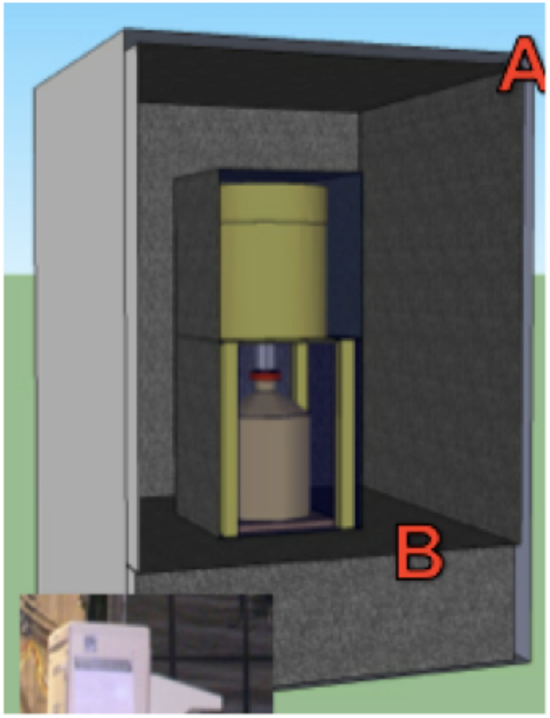
Detectors for **neutrino-induced neutrons**

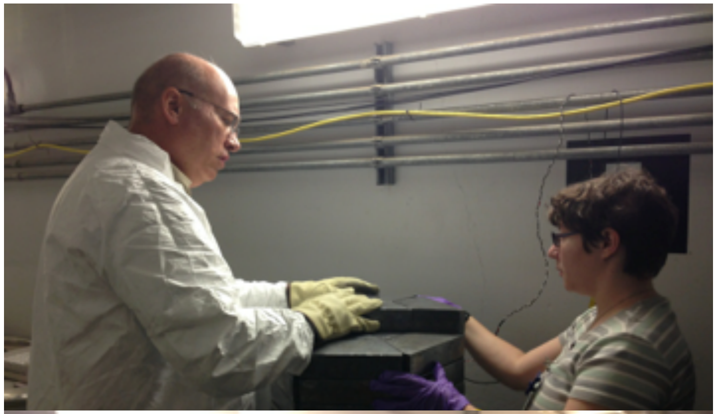
Wish First ν's at SNS!

Dual-phase LXe



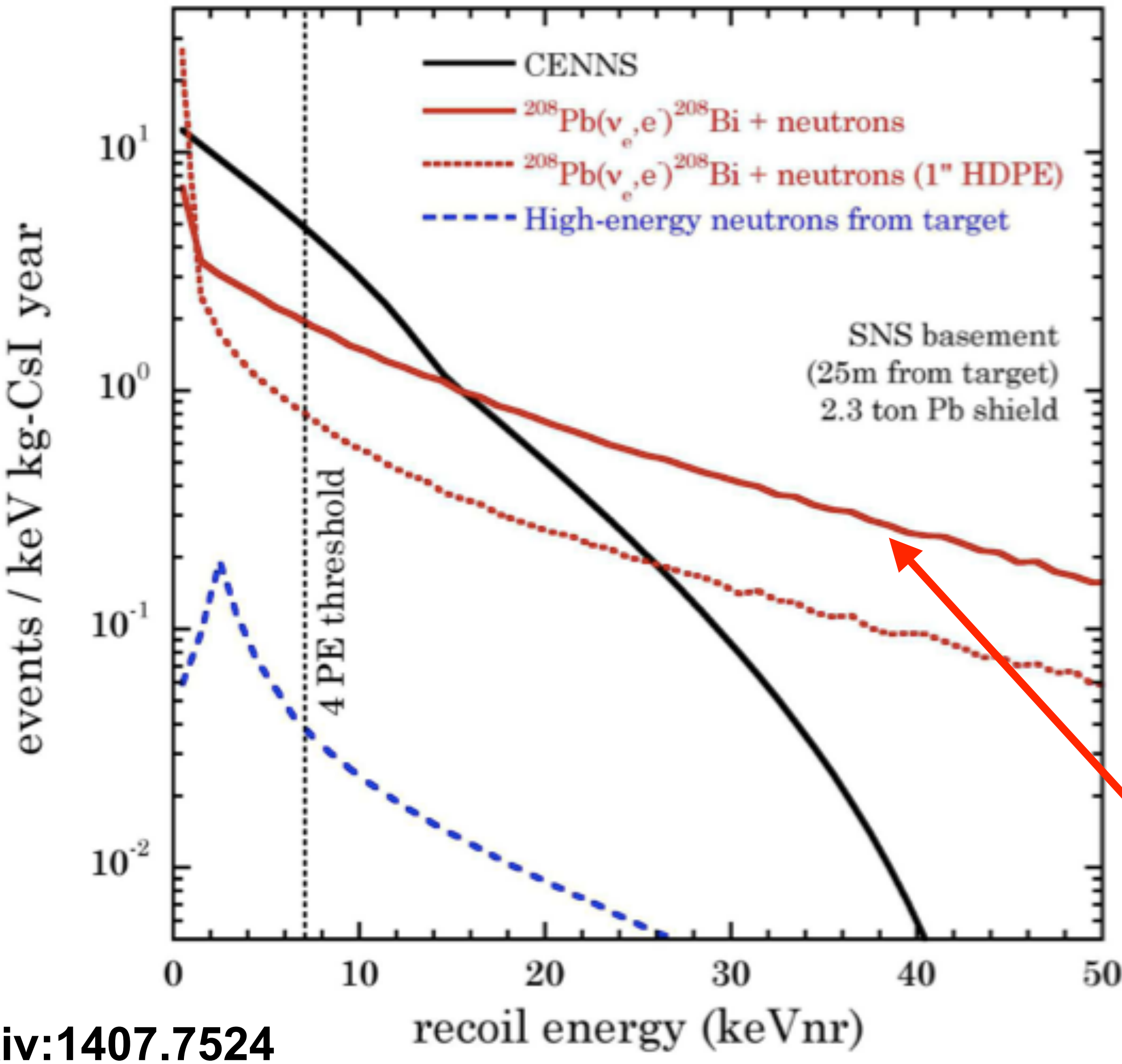
HPGe





Neutrino Induced Neutrons (NIN)

- 25m from the target : ~1.7×10^6 /cm^2/s
- Scintillator inside CsI detector lead shield
- Liquid scintillator surrounded by lead (swappable) inside water shield



14 kg CsI already at UChicago

NINs not negligible w/lead shield! ➔ need careful shielding design

arXiv:1407.7524

HALO: use the NIN for detection of SN

$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

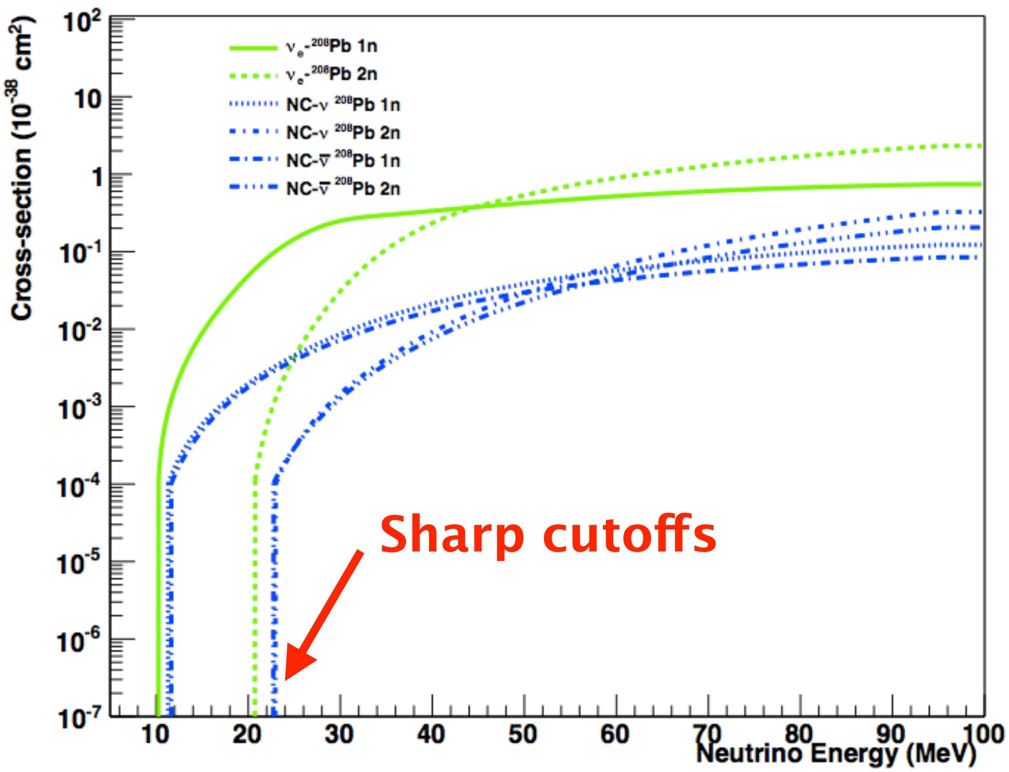
1n, 2n emission

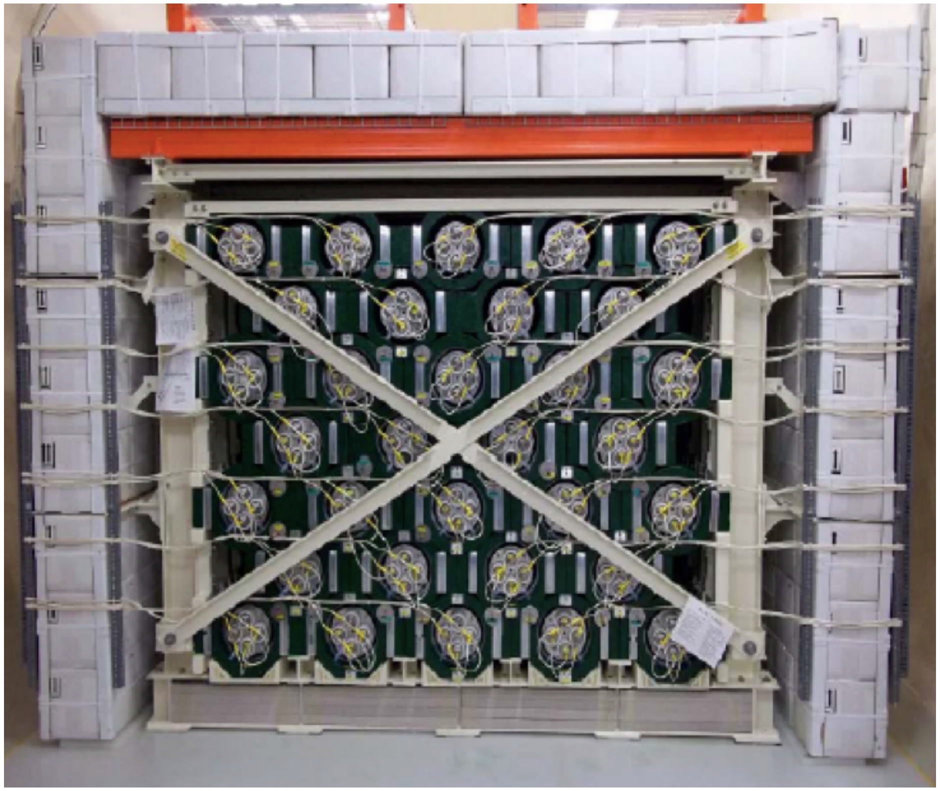
$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC

1n, 2n, γ emission

Helium And Lead Observatory (HALO) at SNOLab: Supernova detector

- 79 tonnes of lead instrumented with ^3He neutron counters w/HPDE moderator + water shield





Argon Target: Theoretical Calculations

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

- Shell-Model, Super-allowed F transition: Ragahvan, and Bahcall et al. (1986)
- Shell-Model, +GT transition: Ormand et al. (1996)
- Shell-Model, more GT transition: M. Bhattacharya et al. (1998)
- Random Phase Approximation (RPA) forbidden transitions: Langanke et al. (2003)
- Local Density Approximation (LDA) : Singh et al. (2004)
- Hybrid Model, Shell-Model+RPA: T. Suzuki (2011)

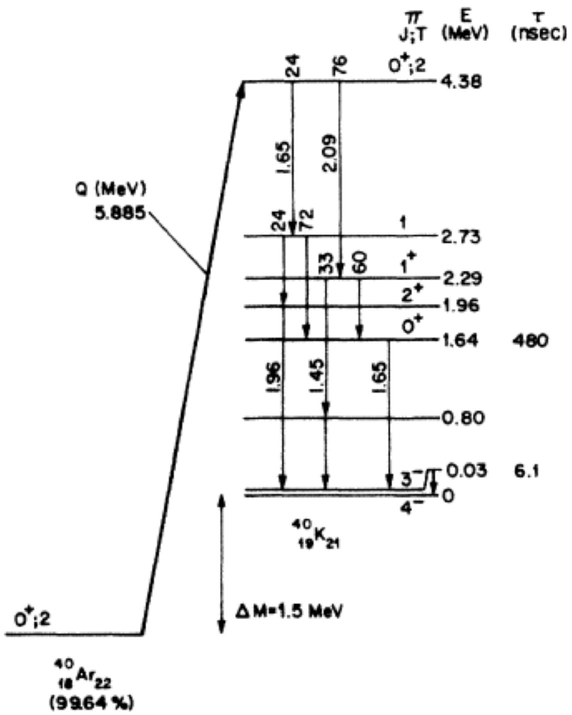
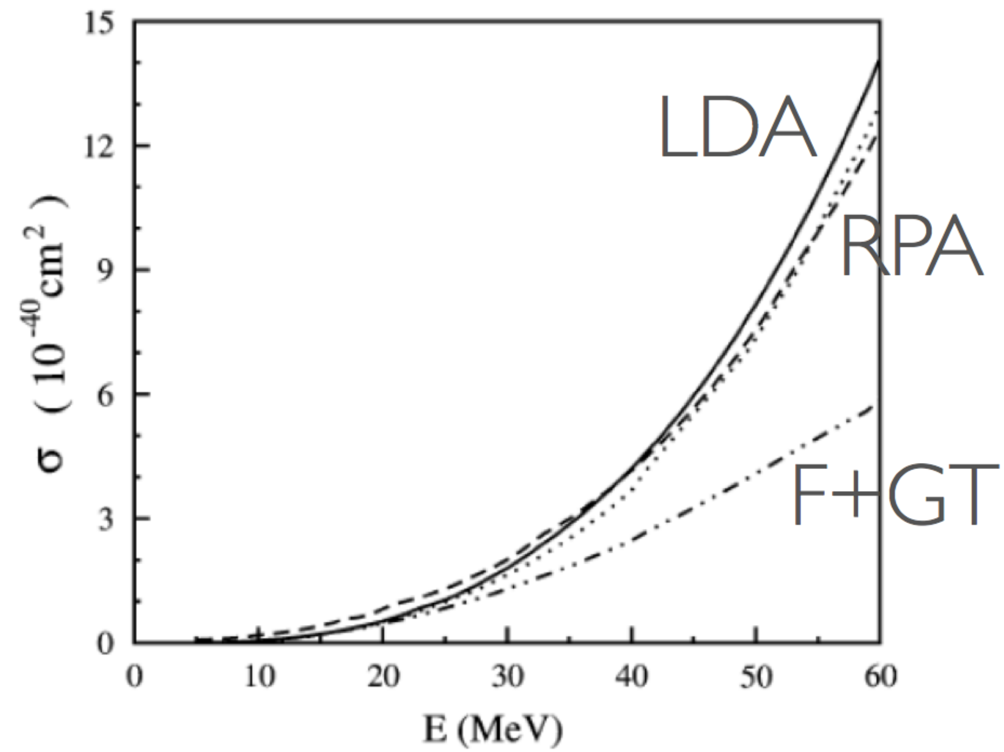
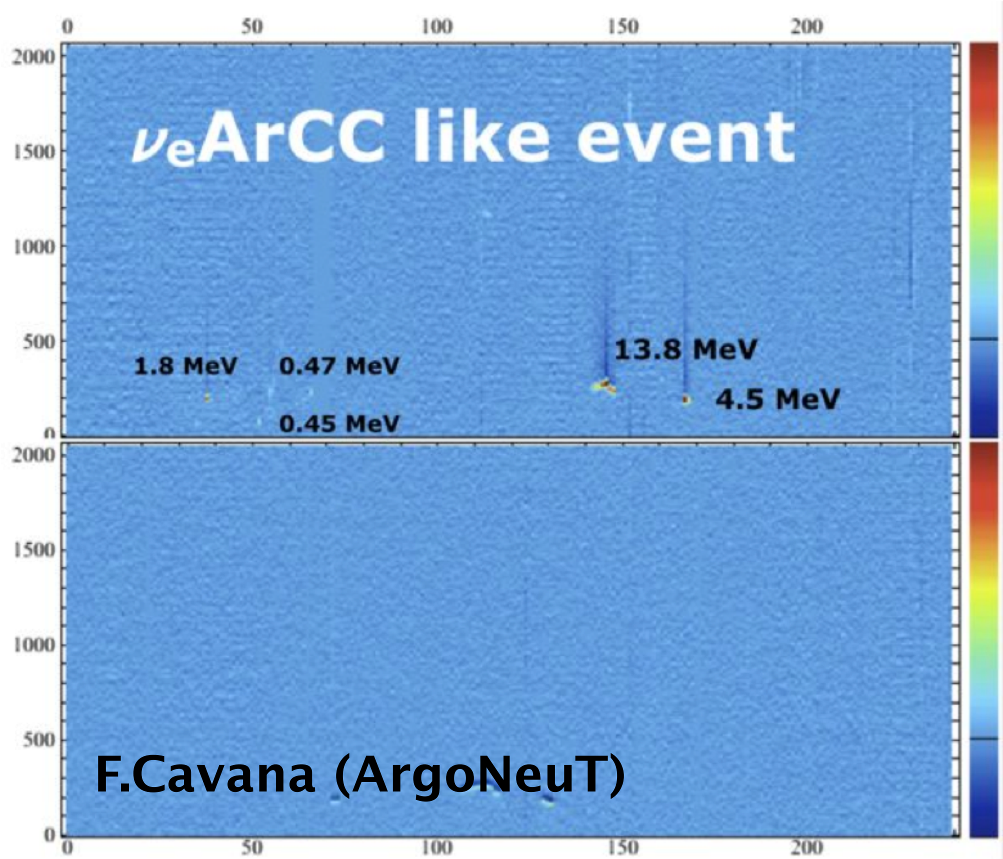
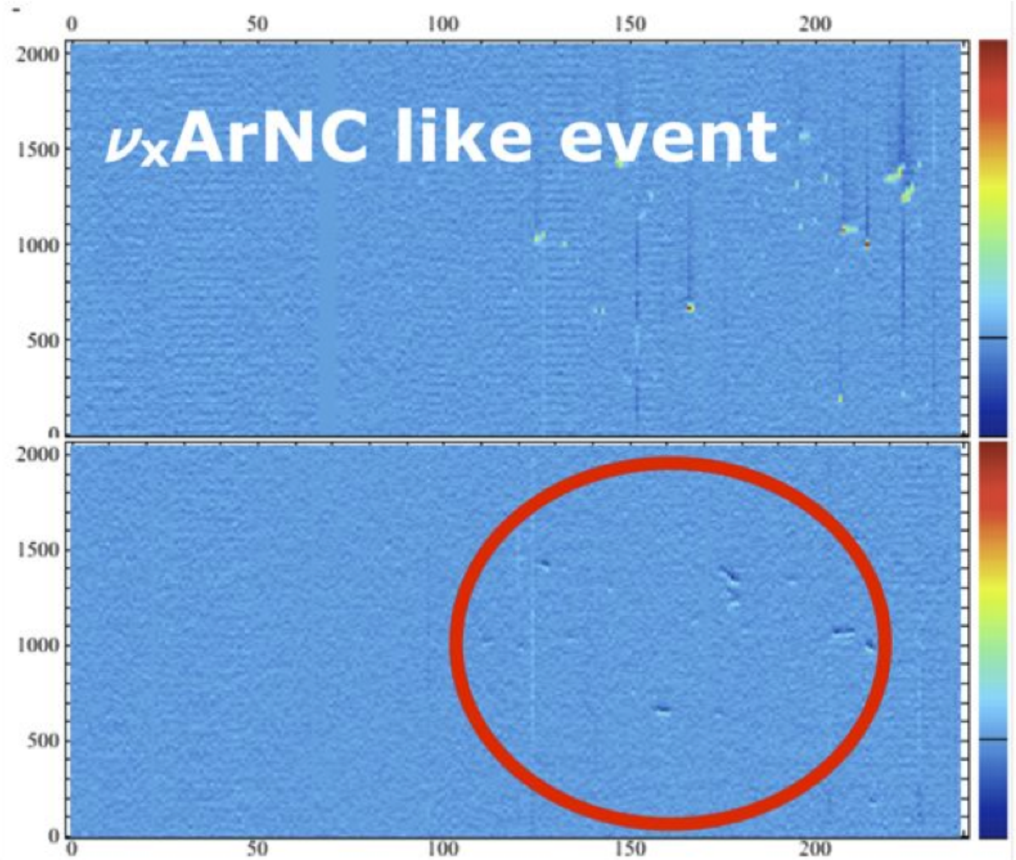


FIG. 1. Level scheme of ^{40}Ar-^{40}K relevant to ν_e capture in argon.



LArTPC: Low Energy Neutrino Interactions



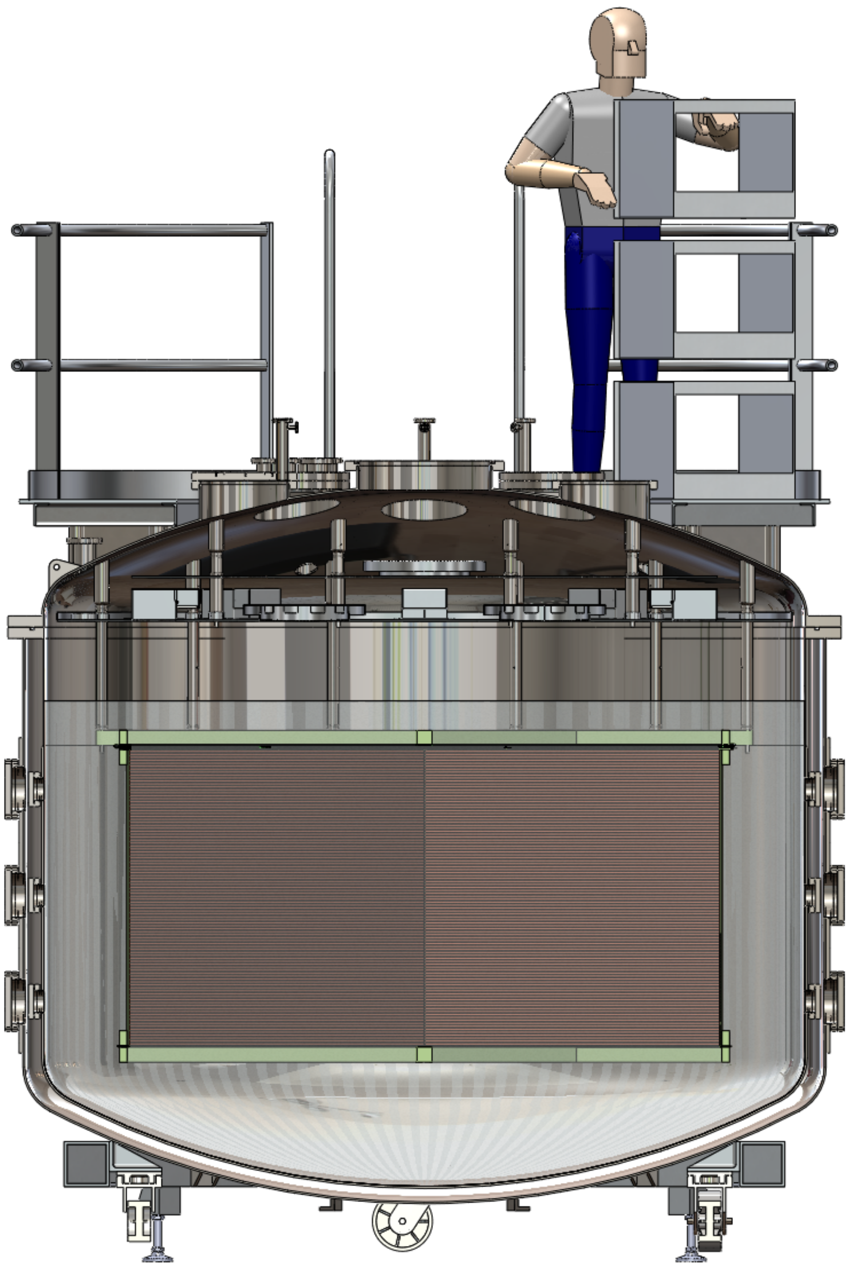


$$\nu_e\text{ArCC}: \quad \nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$
$$\bar{\nu}_e\text{ArCC}: \quad \bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$$
$$\text{ES}: \quad \nu_x + e^- \rightarrow \nu_x + e^-$$
$$\nu_x\text{ArNC}: \quad \nu_x + {}^{40}Ar \rightarrow {}^{40}Ar^* + \gamma$$

Experimental challenges in LArTPC

- Events are elections and gammas
- Long track for CC events is ~10 wires and gammas and electrons “spots”
- Photo detection might help

Argon Target: CAPTAIN-BNB



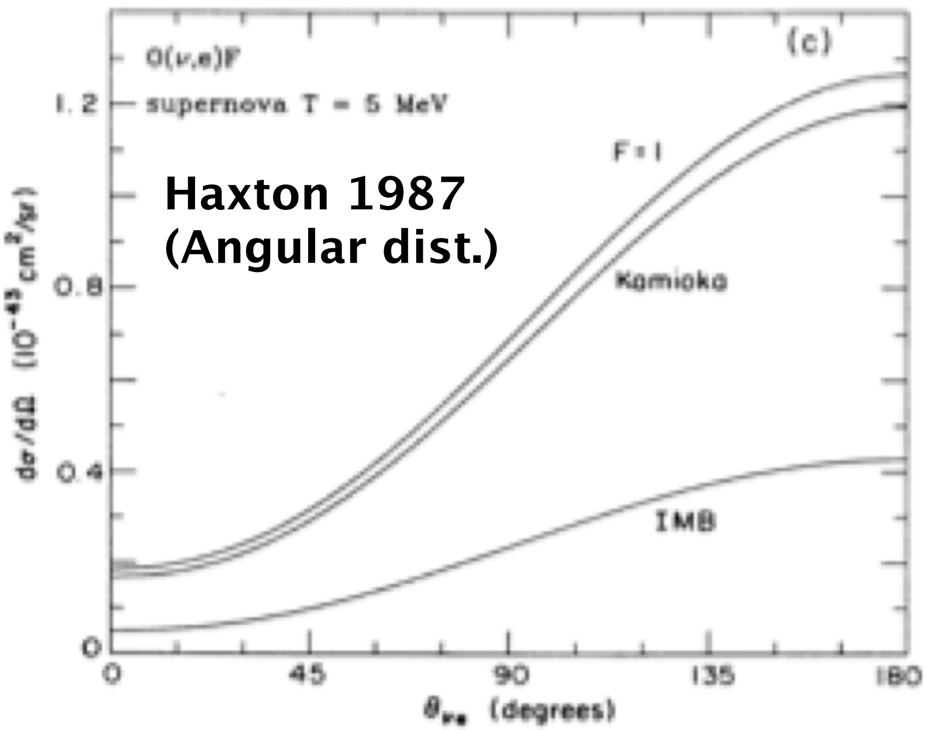
- **LANL LDRD project (arXiv:1309.1740)**
  - R&D for particle interactions in TPC
  - Designed for easy transportation
  - Capacity: ~7700L (10ton full LAr)
    ~5ton LArTPC active region
  - All cryogenic and instrumentation connections made through top head
  - Detector assembly and test in 2015

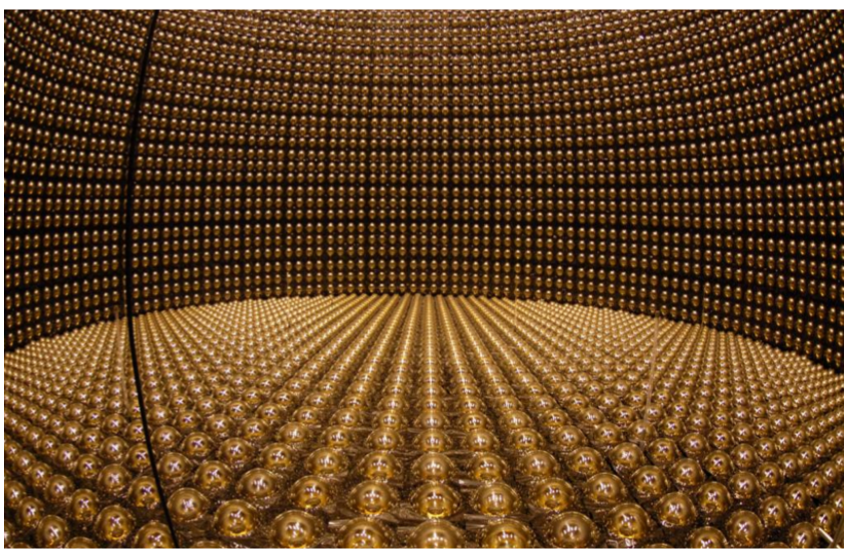
- The detector maybe placed at BNB off-axis and measure ν cross-sections relevant to supernova physics
  1-year operation at BNB (17kW)

  Charged-current absorption
  $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ (~250 events)
  Neutral-current excitation
  $\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$ (~100 events)

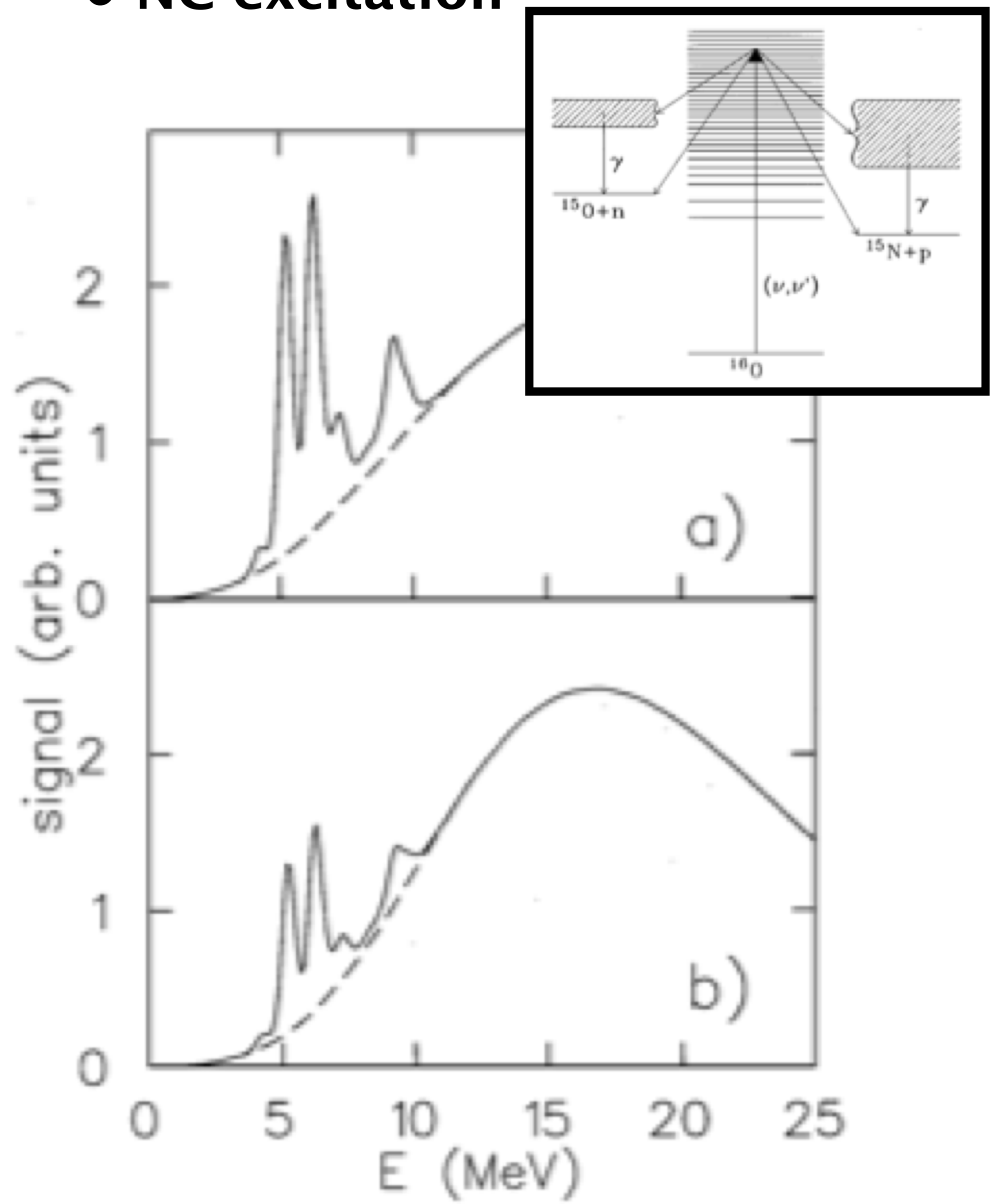
- **Fermilab PAC (Jan 2015)**
  - CAPTAIN-BNB proposal
    waiting for the PAC response

- CC interactions





- NC excitation



Langanke et al. (1996)

Summary

- Pion-DAR sources will provide high-intensity
  low energy neutrinos in the 10s of MeV range.
  - The sources under consideration are:
    SNS at ORNL, BNB at FNAL, MLF at J-PARK

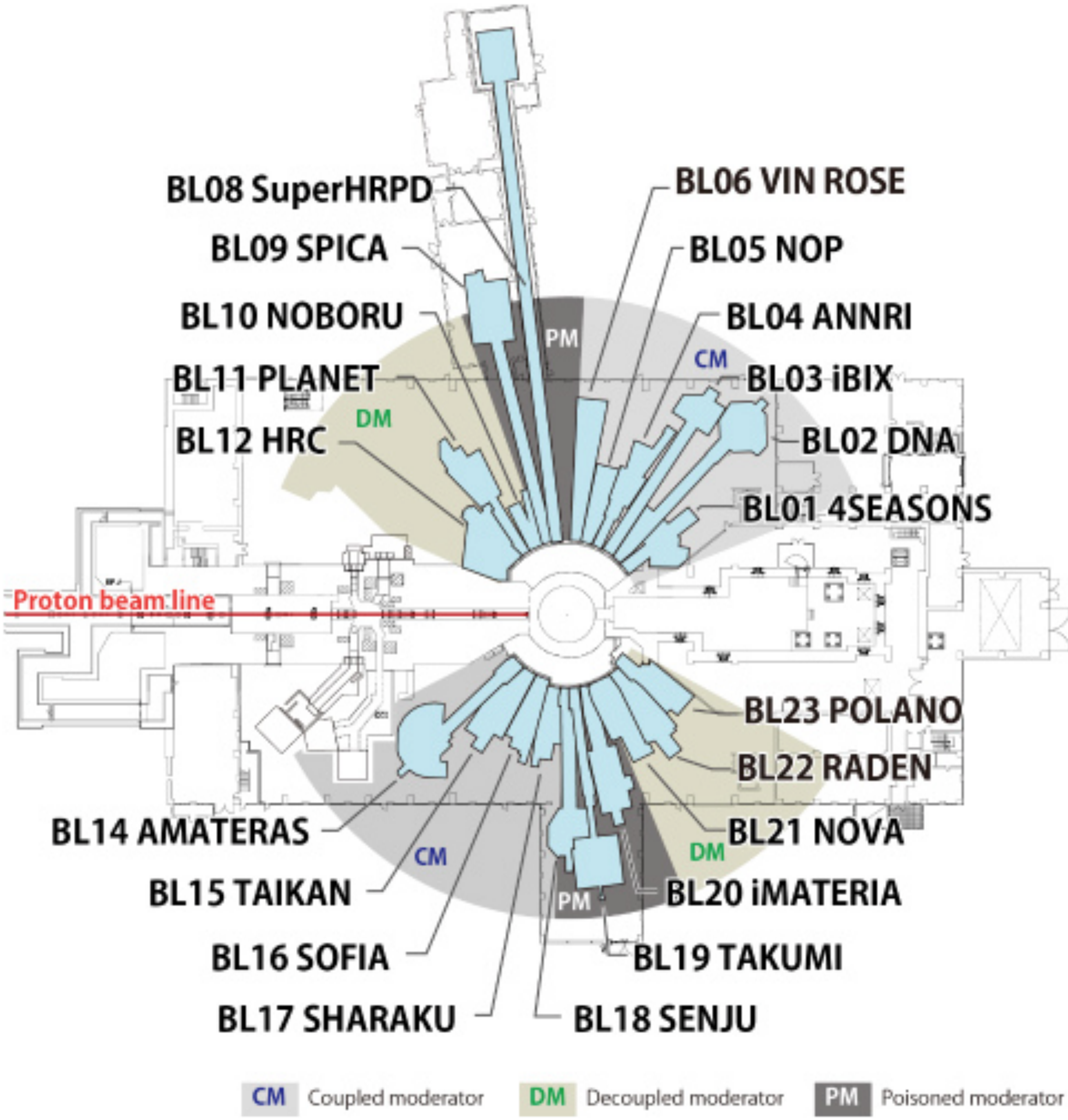
- There are ongoing efforts for the cross-section measurements:
  Supernova neutrino-relevant
  Discover the CEvNS

- Flux uncertainty of neutrino source — need improved study

- Success of the initial study would open up new opportunities
  of low energy neutrino physics

Backup

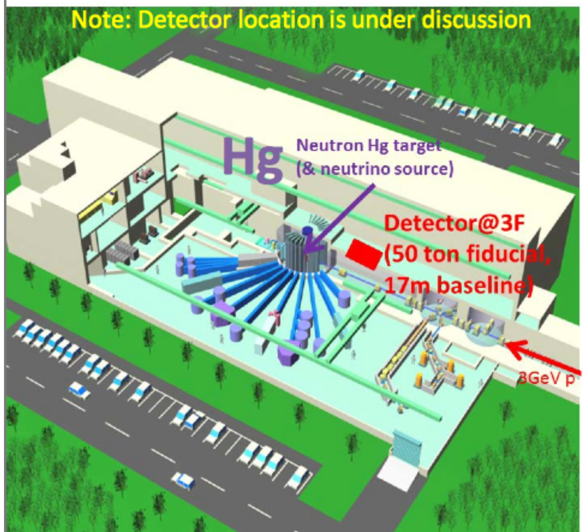
J-Park (Japan) Material and Life Science Facility



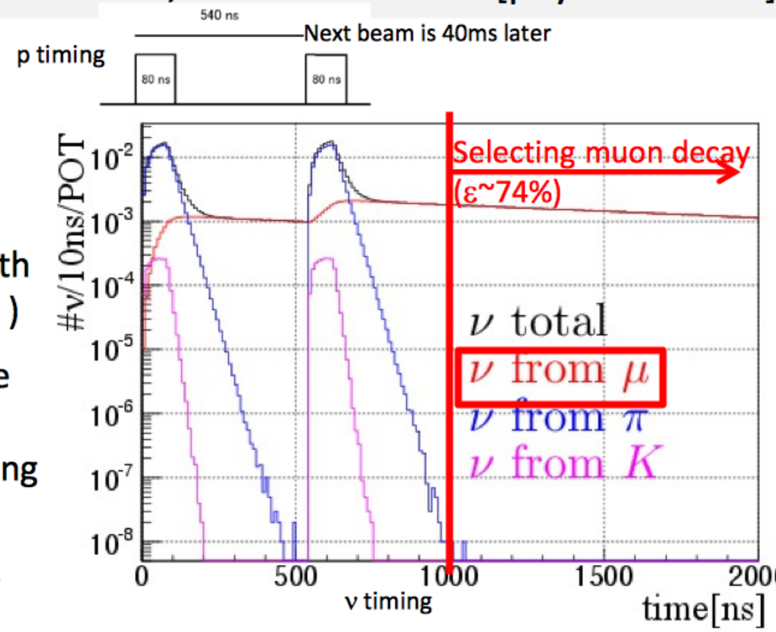
- 3GeV rapid cycling synchrotron
  - 600ns pulsed beam spill
- Spallation neutron target
  - Mercury target
- 1MW, 25 Hz rep-rate
- 80ns wide pulse, 540ns apart
- Proton On Target = 3×10^{22} POT / year
- 0.27 ν-production per proton
- ν Flux = 6×10^{6} ν /s/cm^2 (@17m)

Sterile neutrino search @MLF (proposal in 2013)

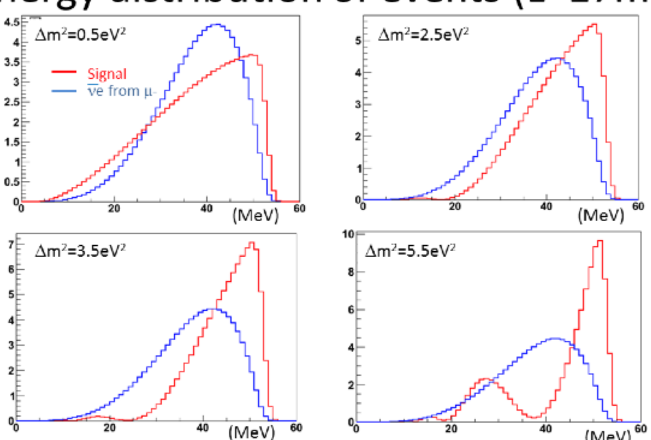
M. Harada *et al*, arXiv:1310.1437 [physics.ins-det]



- J-PARC P56 aims to confirm or refute the neutrino oscillation with sterile neutrino($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
- With gating the time we can use ultra-pure neutrinos from stopping μ^+ (top-right)
- Energy distortion → sig vs BKG separation (bottom-left)



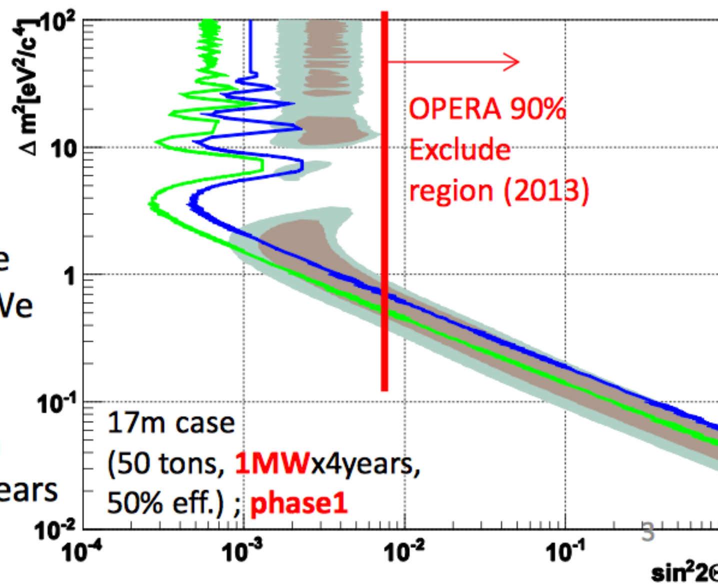
Energy distribution of events (L=17m)



$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot \boxed{\Delta m^2} \cdot L}{E_\nu}\right)$$

- Energy is smeared by 15%/sqrt(E) (detector E resolution)

- Sensitivity of P56 (right); blue 5σ, green 3σ. We conclude LSND region (brown (90%CL) & green (99%) within 4 years



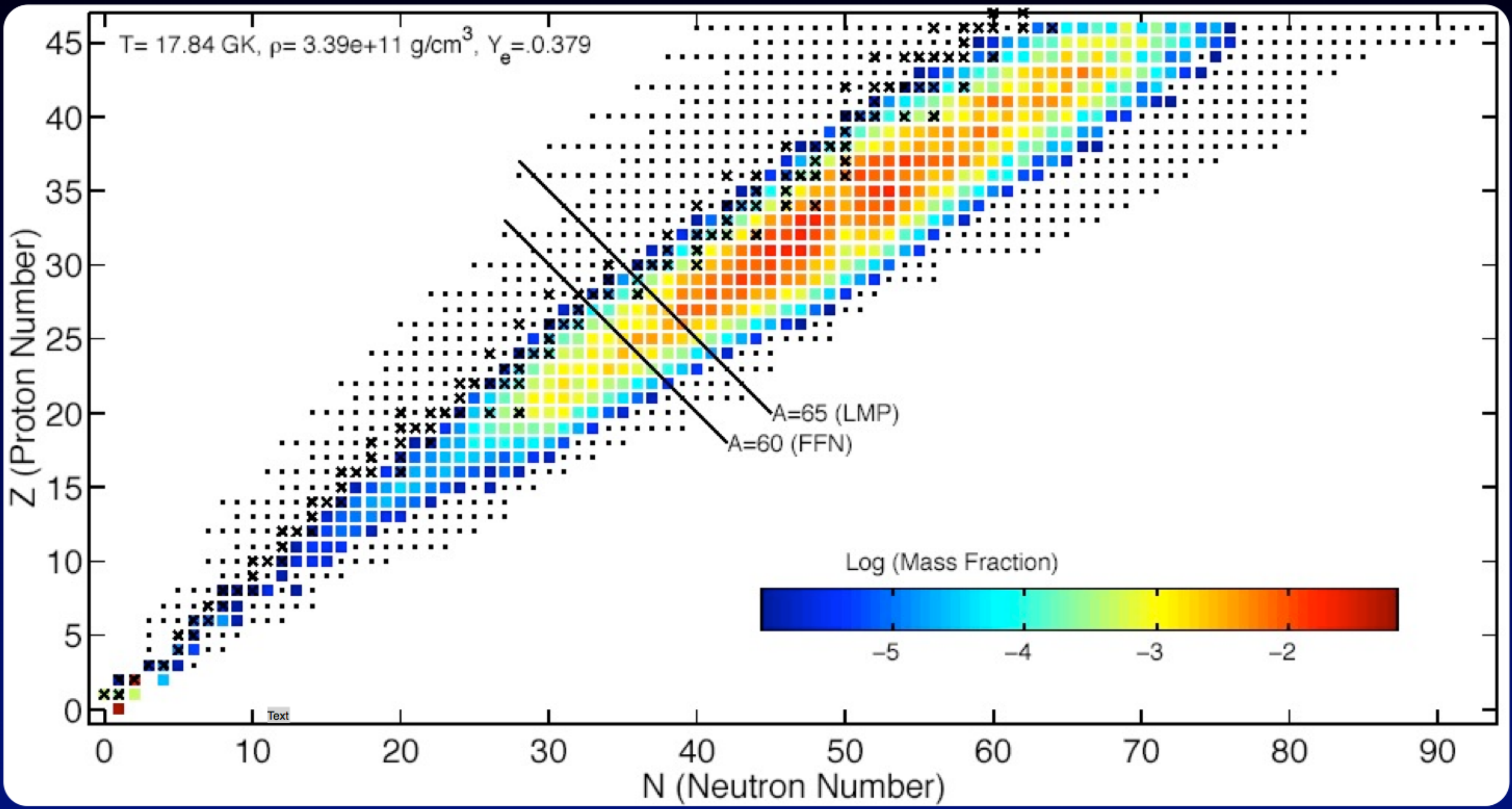
T. Maruyama (2014 MLF-PAC)

J-PARK (P56) Background Measurement

Source	contents	#ev./50tons/4years (left; proposal, right; present)	comments
background	$\overline{\nu}_e$ from μ-	377 → 149	Baseline; 17m -> 24m additional cuts; 77%
	$^{12}C(\nu_e,e-)^{12}N_{g.s.}$	38 → 10	
	Beam fast neutrons	Consistent with 0 0.2→ <8(90%CL UL)	Based on real meas.
	Fast neutrons (cosmic)	42 → 22	
	Accidental	37 → 20	Based on real meas.
signal		881 → 301	Δm^2=3.0(left), 2.5(right)
		377 → 215	Δm^2=1.2, $\sin^2 2\theta$=0.003

T. Maruyama (2014 MLF-PAC) ➜ Waiting for the PAC response

WHICH NUCLEI ARE PRESENT?



Neutron-Rich Nuclei with A ≤ 120 are present in collapsing core.

W. R. Hix, ν@SNS, Oak Ridge, May 2012

What is the right place to look for Neutrino coherent scattering?

Nuclear reactor **or** **DAR facility**

- Huge neutrino flux

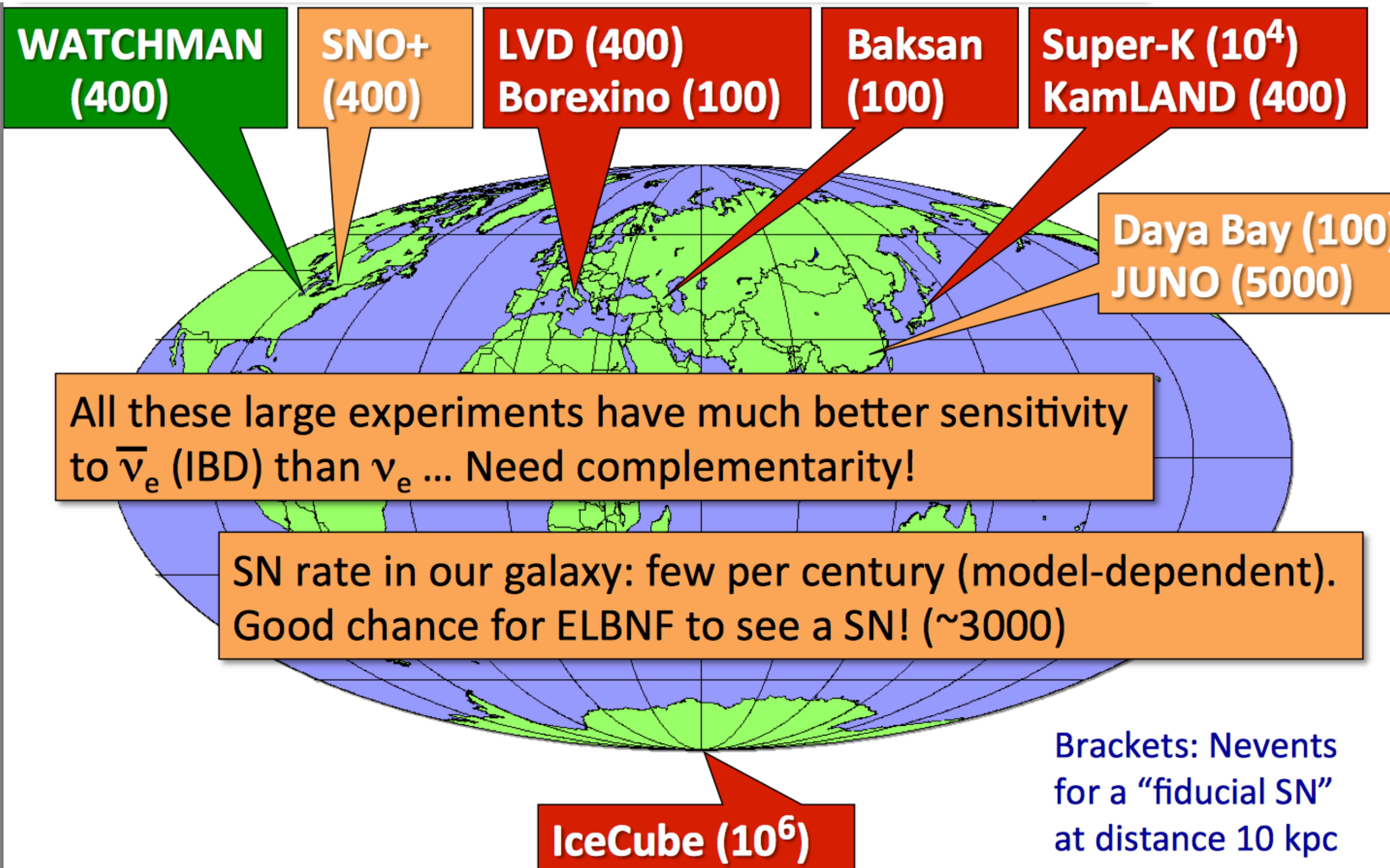
- Just right energy range
- Pulsed structure
- Characteristic time distribution
- Multiple flavors
- Wide mass range of targets

- Low energy: difficult to use heavy targets
- No pulsed structure

- Not as large flux as at reactor

Yuri Efremenko (WINP2015)

Supernova Detectors



All these large experiments have much better sensitivity to $\overline{\nu}_e$ (IBD) than ν_e … Need complementarity!

SN rate in our galaxy: few per century (model-dependent). Good chance for ELBNF to see a SN! (~3000)

Brackets: Nevents for a "fiducial SN" at distance 10 kpc

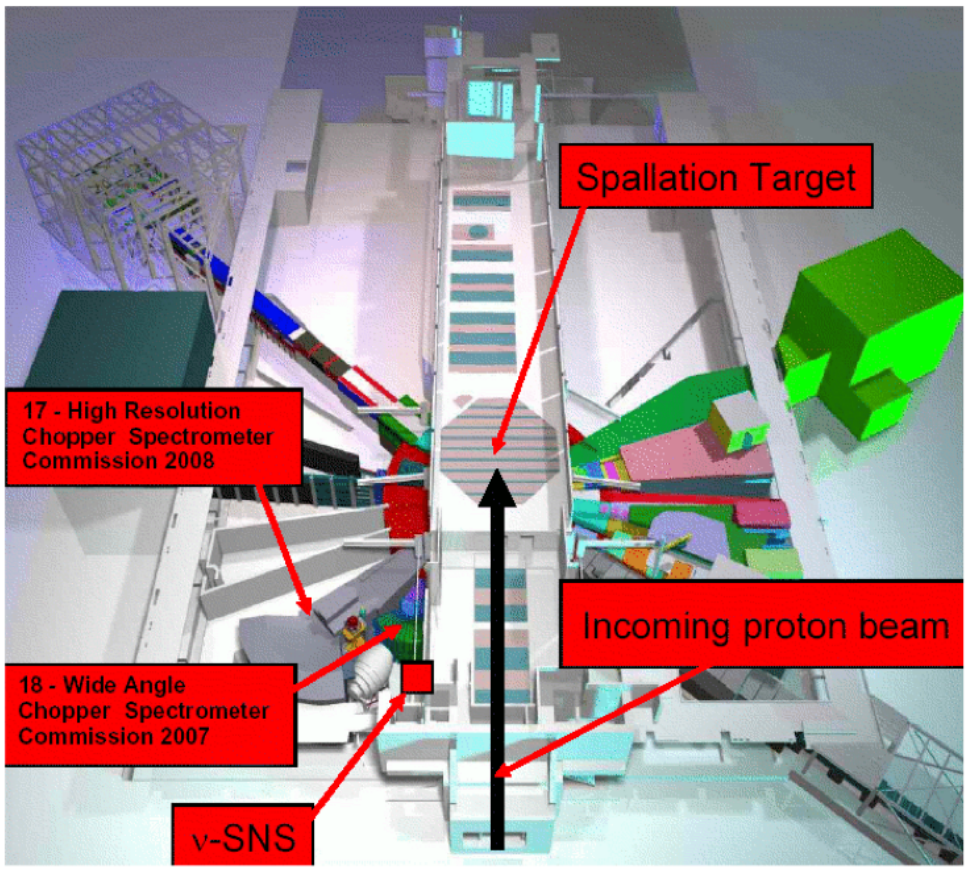
I.Stancu

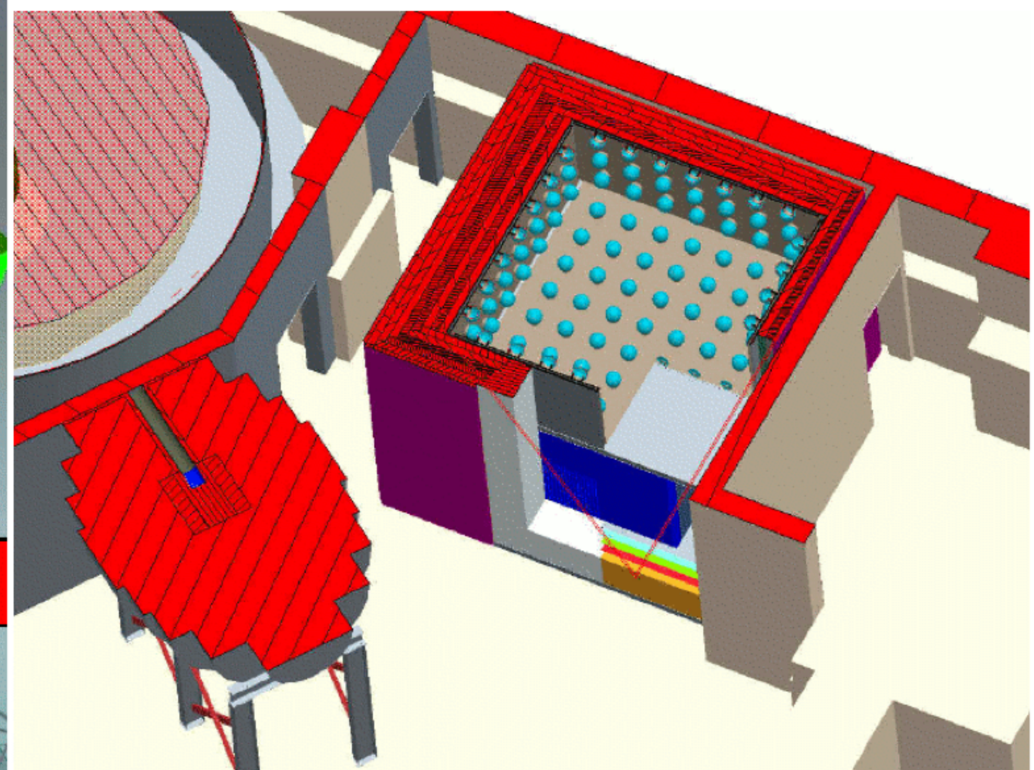
NuSNS (Neutrinos at the SNS)

Conventional ~10 ton detectors w/ few MeV thresholds:

- -liquid target + PMTs
- -strawtube gas tracker+ target sheets
- -cosmic ray veto

} changeable targets





Fermilab Booster Neutrino Beam (BNB) Target Building